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THESIS

INVESTIGATION OF DESIGN CONSIDERATIONS FOR TELEMETRY, TRACKING, AND COMMAND (TT&C) ANTENNA SYSTEM ON NAVAL POSTGRADUATE SCHOOL ORION MINI-SATELLITE

by

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Investigation of Design Considerations for Telemetry, Tracking, and Command (TT&C) Antenna System on Naval Postgraduate School Orion Mini-Satellite

by

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ABSTRACT

This thesis investigates design requirements for the telemetry, tracking, and command (TT&C) antenna system on the proposed Naval Postgraduate School Orion mini-satellite. Initial design criteria were developed by examination of the satellite itself, including launch vehicles, orbital profiles, and ground interfaces. After consideration of these design constraints, a review of commercially available TT&C antennas was conducted to determine compatibility with Orion, culminating in recommendation of the conical log-spiral as the primary candidate for use on the spacecraft. The conical log-spiral is a low cost, space-qualified antenna capable of providing broadband omni-directional circularly polarized radiation from space, while fulfilling pattern coverage, space-ground link power margin, and transmitter-receiver isolation requirements for the Orion mini-satellite.

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I. INTRODUCTION

A. MOTIVATION FOR STUDY

The space program of the United States has become largely focused on the use of large, high-value satellites. A substantial number of commercial, scientific, and military payloads are not even launched, due primarily to the high cost of satellites. Opening space to a larger group of users requires the development of small, relatively inexpensive, generic satellites which could be readily adaptable to a wide variety of missions and orbits. The proposed Naval Postgraduate School (NPS) Orion Mini-satellite will be a prototype low cost, general purpose space vehicle built from commercially available components.

B. STATEMENT OF PROBLEM

The stated general purpose nature of the Orion mandates that the design must support fully autonomous satellite operation, with a relatively independent payload module. Support functions which must be provided by the vehicle to the payload module include propulsion for orbital insertion and attitude control; telemetry, tracking, and control (TT&C); data processing and storage; and electrical power. [Ref. 1: p. 4]

This thesis addresses design considerations for the antenna package on the TT&C subsystem, culminating in recommendation of an optimum antenna for the NPS mini-satellite. Specific areas investigated in this design proposal include antenna compatibility with the spacecraft itself, gain requirements and antenna radiation patterns compatible with proposed orbits and ground stations, and isolation requirements between transmit and receive modes on the antenna.

After a review of commercially available TT&C antennas, the two most likely candidate TT&C antennas for the spacecraft appear to be the conformal microstrip array and the conical log-spiral. Of these, the conical log-spiral proves to be the most qualified, fully capable of meeting the requirements of the Orion mini-satellite.

II. ORION MINI-SATELLITE

A. DESCRIPTION OF SATELLITE

1. Spacecraft Specifications

The overall design for the Orion mini-satellite is still rather fluid at the present time. Assumptions concerning the final design and mission profile for Orion are based primarily on the "Management Plan" for the NPS Mini-Satellite Program, prepared by Marty R. Mosier, Orion Staff Eningeer, in March of 1987, or on later conversations between the author and Marty Mosier.

The Orion is primarily being designed for use in the National Aeronautics and Space Administration (NASA) Space Shuttle "Get Away Special" (GAS) experimental launch program. Payloads intended for GAS launch are constrained in size by the canister, or payload container, within the Shuttle bay. The Orion will be well within GAS canister limitations. Current designs call for a vehicle which is cylindrical in shape, with a height of 35 inches and a diameter of 19 inches. The satellite will weigh approximately 250 pounds, and will be able to support a payload of 50 to 130 pounds. [Ref. 1: p. 4]

The Orion will be a spin-stabilized satellite with its spin axis perpendicular to the plane of it orbit. In

spin-stabilization the spacecraft is rotated while in orbit at a rate commonly between 30 and 100 rpm. The satellite therefore acts as a gyro wheel with high angular momentum, resulting in attitude stiffness or stability. Four 80 inch booms have been added to the Orion for additional stability. Spin-stabilization of a cylindrical satellite is shown in Figure 2.1. Although spin-stabilization is the simplest form of attitude control, it places added demands on antenna design: onboard antennas must either be omni-directional resulting in considerable power loss from radiation into free space, or be electrically or mechanically despun so that the net effect is a stationary antenna beam relative to earth. [Ref. 3: p. 304]

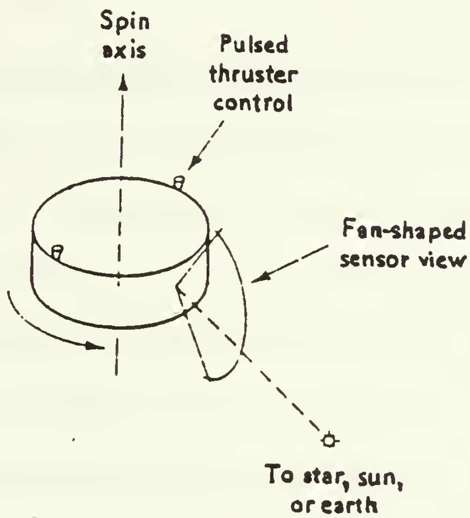

Figure 2.1 Spin-stabilation [Ref. 2: p. 115]

Power requirements are a prime consideration in designing a mini-satellite, due largely to a limited surface area available for solar cells. This problem becomes even more critical for a cylindrical spin-stabilized satellite, as only approximately 30 percent ($1/\pi$) of the incident solar radiation is available for conversion to electrical energy at any one time [Ref. 4: p. 119]. Present plans call for Orion to be powered by a 60 watt solar cell system with a battery capable of storing 180 watt-hours of electrical power. In order to produce this amount of energy, nearly the entire cylinder will be covered with strings of 2 by 4 cm solar cell wafers. The limited surface area has a major impact on placement of the antenna on the vehicle, as will be seen later.

2. Transmitter and Receiver Specifications

The Orion is being designed for tracking from earth via the U.S. Air Force Space-Ground Link System (SGLS). On board TT&C transmitters and receivers will therefore need to be SGLS compatible. The SGLS downlink consists of two carriers which can be received simultaneously at the ground station and are used to convey range data, payload data, and telemetry data. The two signals are referred to as Carrier 1 and Carrier 2. Carrier 1 is the pilot signal for normal antenna auto tracking, range and range rate tracking, and low speed pulse code modulation (PCM) analog telemetry.

Carrier 2 is set at a 5 MHz offset below Carrier 1, and provides one digital stream for digital telemetry. It operates at a rate from 128 kbps to 1.024 Mbps using Phase Shift Keying (PSK). [Ref. 5: p. 2.3-1] SGLS operates in the S-band, with uplink frequencies from 1750 to 1850 MHz and downlink frequencies between 2200 MHz to 2300 MHz. Table 2.1 lists the SGLS Channels and associated frequencies.

A commercially available SGLS transmitter, receiver, and transponder from Motorola is currently being utilized in space in a number of Department of Defense (DoD) satellites, such as FLTSATCOM, GPS, and DSCS III, and has been proposed for use in Orion. This unit is highly reliable and is modular in design, allowing it to be easily configured to a mini-satellite platform. The Motorola SGLS satellite transmitter is capable of providing 3.0 watts of RF power into a 50 ohm load with a VSWR of less than 2:1, while the receiver is a second order phase-locked loop having an acquisition range of plus or minus 100 kHz and a lock range of 4 kHz. Receiver sensitivity is -113 dBm with a noise figure of 5 dB. [Ref. 6: p. 4]

3. Launch and Oribital Considerations

Although designed primarily for GAS launch from the Space Shuttle, the Orion is also compatible with a number of small expendable launch vehicles, or can be flown as a secondary payload on larger vehicles. [Ref. 7: p. 5] As such, the Orion TT&C subsystem must be capable of

TABLE 2.1

SGLS RF FREQUENCIES [Ref. 5: p. 2.3-15]

SGLS Channel	Uplink Frequency MHz (+0.002%)	Downlink Frequencies MHz (nominal) Carrier 1	Carrier 2
1	1763.721	2202.500	2197.500
2	1767.725	2207.500	2202.500
3	1771.729	2212.500	2207.500
4	1775.733	2217.500	2212.500
5	1779.736	2222.500	2217.500
6	1783.740	2227.500	2222.500
7	1787.744	2232.500	2227.500
8	1791.748	2237.500	2232.500
9	1795.752	2242.500	2237.500
10	1799.756	2247.500	2242.500
11	1803.760	2252.500	2247.500
12	1807.764	2257.500	2252,500
13	1811.768	2262.500	2257.500
14	1815.772	2267.500	2262.500
15	1819.775	2272.500	2267.500
16	1823.779	2277.500	2272.500
17	1827.783	2282.500	2277.500
18	1831.787	2287.500	2282.500
19	1835.791	2292.500	2287.500
20	1839.795	2297.500	2292.500

communicating with appropriate ground stations from a variety of orbits before insertion into final orbit. The launch geometry for expendable vehicles and for the Space Shuttle are depicted in Figures 2.2 (a.) and (b.) respectively. In both cases satellites must be placed in an elliptical transfer orbit with its perigee normally between 100 to 300 kilometers and its apogee on the final orbit. For a Shuttle launch, the satellite is first placed in a low earth circular parking orbit. On board thrusters must then propel the satellite into its transfer orbit. Expendable launch vehicles, on the other hand, may be used to carry the satellite directly into transfer orbit. [Ref. 4: p. 89]

Dependent upon the mission of the payload, the final orbit of the Orion must be flexible if the satellite is to be a true multi-purpose satellite. Current plans envision the Orion's most likely mission profile to be a medium altitude 400 nautical mile circular orbit, although the possibility exists for a mission profile with an elliptical orbit having an apogee of 2200 nautical miles and a perigee of 135 nautical miles. Inclination of the final orbit may be from 28 degrees, the latitude of Cape Canaveral, up to a polar earth orbit of 90 degrees. Once again, the TT&C system, and specifically the on-board antenna package, must be designed such that the Orion will be able to maintain contact with earth for all of these orbits.

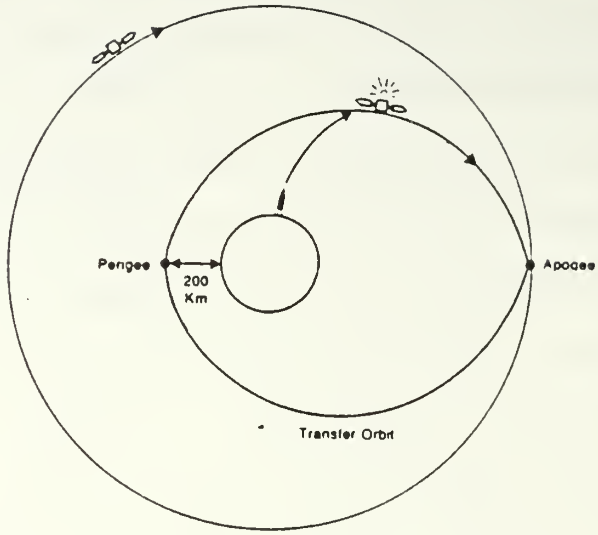

Figure 2.2 (a.) Launch Geometry - Expendable Vehicle
[Ref. 4: p. 90]

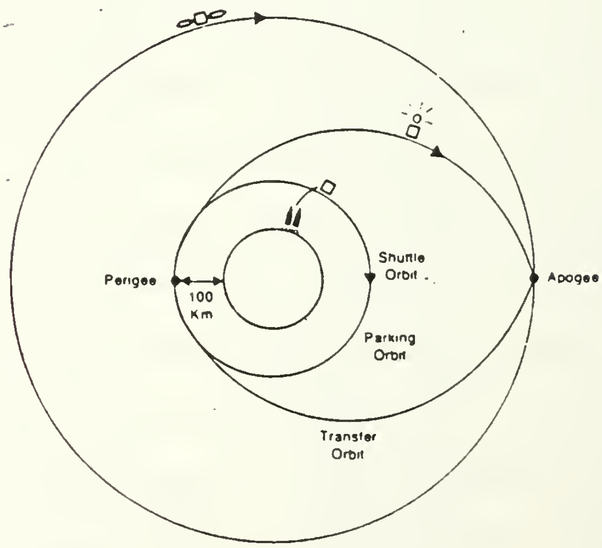

Figure 2.2 (b.) Launch Geometry - Space Shuttle
[Ref. 4: p. 90]

B. GROUND INTERFACE

1. Air Force Satellite Control Network

As has been mentioned, the Orion satellite will communicate to the earth via SGLS. SGLS is designed to interface directly with the U.S. Air Force Satellite Control Network (AFSCN), whose prime function is to provide tracking, telemetry, command, and communication functions in support of national space programs. AFSCN manages a world wide network of twelve Remote Tracking Stations (RTS), located at seven geographically dispersed locations. These stations are listed in Table 2.2. In addition, there are AFSCN control centers at the Satellite Operations Center (SOC) located in Colorado Springs, Colorado, and at the Satellite Test Center (STC) located at Sunnyvale, California. [Ref. 5: p. 1.2-1]

The signals which may be received at a RTS are limited to a large degree by the characteristics and capabilities of the antenna systems employed by the particular tracking station. These antennas, also listed in Table 2.2, under the appropriate RTS, are all intended for interface with SGLS.

2. AFSCN TT&C Antennas

a. 60 Foot TT&C Antenna

The stations in New Hampshire (NHS), Hawaii (HTS), Vandenberg (VTS), and the Indian Ocean (IOS) are all equipped with a 60 foot parabolic TT&C antenna system. This system

TABLE 2.2

REMOTE TRACKING STATIONS [Ref. 5: p. 1.2-2]

Tracking Stations	N Latitude	E Longitude
NHS - New Hampshire (Manchester)		
TT&C - 60 ft	42:56.9	288:22.4
TT&C - 46 ft	42:56.7	288:22.2
VTS - Vandenberg AFB (Lompoc, California)		
TT&C - 60 ft	34:49.4	239:29.9
TT&C - 46 ft	34:49.6	239:29.7
HTC - Hawaii (Kaena Point, Oahu)		
TT&C - 60 ft	21:33.8	201:45.5
TT&C - 46 ft	21:34.1	201:44.3
GTS - Guam		
TT&C - 60 ft	13:36.9	144:52.0
TT&C - 46 ft	13:36.95	144:51.3
IOS - Indian Ocean (Mahe, Seychelles)		
TT&C - 60 ft	-4:40.3	55:28.7
TTS - Thule (Greenland)		
TT&C - 46 ft	76:30.9	291:24.0
TT&C - 14 ft	76:31.0	291:24.0
TCS - Oakhanger (England)		
WAT - 60 ft	51:6.8	359:6.3

is designed to receive right hand circularly polarized (RHCP) signals. Linearly polarized signals are received at a loss of 3 dB in signal strength. The stations at HTS and IOS will also operate with left hand circularly polarized signals. Signal characteristics are as follows: [Ref. 5: p. 2.2-4]

<u>TRANSMIT</u> (uplink - at transmitter output)

RF: 1.75 to 1.85 GHz band

BEAMWIDTH: 0.70 degree $\pm$ 0.25 degree

GAIN: 42.7 dB effective (includes radome)

<u>RECEIVE</u> (downlink - at anetenna aperture)

RF: 2.2 to 2.3 GHz band

BEAMWIDTH: 0.55 degree $\pm$ 0.25 degree

GAIN: 48.2 dB effective (includes radome)

<u>SYSTEM NOISE TEMPERATURE</u> (at antenna aperture)

340 degrees K (for SGLS)

b. 60 Foot Guam Tracking Station TT&C Antenna

The Guam Tracking Station (GTS) also has a 60 foot parabolic TT&C antenna, but with characteristics differing from the preceding RTSs. Once again the system is designed for RHC signals, but LHCP signals are not accommodated at GTS. Signal characteristics are: [Ref. 5: p. 2.2-5]

<u>TRANSMIT</u> (uplink - at transmitter output)

RF: 1.75 to 1.85 GHz band

BEAMWIDTH: 0.9 degree $\pm$ 0.25 degree

GAIN: 46 dB effective (includes radome)

RECEIVE (downlink - at antenna aperture)

RF: 2.2 to 2.3 GHz band

BEAMWIDTH: 0.6 degree + 0.25 degree

GAIN: 48 dB effective (includes radome)

SYSTEM NOISE TEMPERATURE (at antenna aperture)

340 degrees K (for SGLS)

c. 60 Foot WAT Antenna

The 60 foot wheel and track (WAT) antenna at Oakhanger, England (TCS) has the same characteristics as the 60 foot parabola at GTS, except for noise temperature. System noise temperature at the antenna aperture is only 200 degrees Kelvin for SGLS signals.

d. 46 Foot TT&C Antenna

Forty-six foot parabolic TT&C antenna systems are found at NHS, VTS, HTS, GTS, and Thule, Greenland (TTS). The 46 foot system will accommodate RHCP, but not LHCP signals. Characteristics are: [Ref. 5: p. 2.2-7]

TRANSMIT (uplink - at transmitter output)

RF: 1.75 to 1.85 GHz band

BEAMWIDTH: 0.90 degree ± 0.20 degree

GAIN: 45 dB effective (includes radome)

RECEIVE (downlink - at antenna aperture)

RF: 2.2 to 2.3 GHz band

BEAMWIDTH: 0.70 degree ± 0.20 degree

GAIN: 47.5 dB effective (includes radome)

SYSTEM NOISE TEMPERATURE (at antenna aperture)

220 degrees K (for SGLS)

e. 14 Foot TT&C Antenna

The last TT&C antenna in the AFSCN is the 14 foot parabolic dish at TTS. This antenna is switchable between RHC, LHC, or vertically polarized signals with no loss. Other characteristics are as follows: [Ref. 5: p. 2.2-8]

TRANSMIT (uplink - at transmitter output)

RF: 1.75 to 1.85 GHz band

BEAMWIDTH: 2.8 degrees ± 0.25 degree

GAIN: 31.5 dB effective (includes radome)

RECEIVE (downlink - at antenna aperture)

RF: 2.2 to 2.3 GHz band

BEAMWIDTH: 2.8 degrees ± 0.25 degree

GAIN: 33.5 dB effective (includes radome)

SYSTEM NOISE TEMPERATURE (at antenna aperture)

376 degrees K (for SGLS)

III. SATELLITE TT&C ANTENNAS

A. DESIGN CONSIDERATIONS

1. General

There are a large number of considerations which need to be taken into account when designing an antenna for use in space. These include normal antenna design parameters such as directivity, gain, polarization, and isolation, as well as the space specific requirements of radiation pattern compatibility with orbit, physical compatibility with launch shroud, ability to withstand vibrational loads during launch, solar wind transparency, space environmental survivability, and low weight. [Ref. 8: p. 213] Additional constraints which are specific to the design of mini-satellites include limited availability of surface area for mounting of antennas, and low cost.

2. Orion Specific

a. Pattern Compatibility With Orbit

A highly reliable TT&C System is vital throughout the operational lifespan of a satellite, but is particularly important during orbital injection and positioning when commands need to be issued to the spacecraft and critical telemetry relayed to the ground. This requires that TT&C antennas must be capable of maintaining communication with

the ground station irrespective of the satellite's attitude relative to earth. The most universally accepted TT&C antennas for use prior to final orbit are therefore omni-directional. [Ref. 4: p. 103]

Although solving the problem of earth coverage during orbital injection or orbit transfer, omni-directional antennas exhibit a significant loss of radiated power into free space, as depicted in Figure 3.1. Larger and more

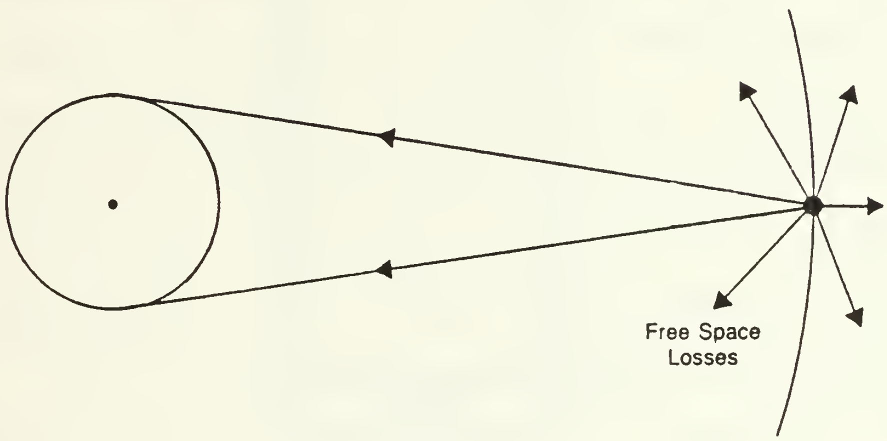

Figure 3.1 Free Space Loss [Ref. 4: p. 98]

elaborate satellites switch to alternate highly directional TT&C antennas with larger gains after becoming stabilized in final orbit. Mini-satellites do not have this luxury; power, size, and weight constraints dictate that only one TT&C package may be employed. In addition, the TT&C antenna package on Orion will also serve as the only means for payload data transmission [Ref. 7: p. 7]. As discussed in Chapter II,

this implies that Orion's TT&C antenna package will need to be compatible with a spin-stabilized orbit. Due to inherent simplicity and compatibility with nearly any orbit, an antenna having an omni-directional radiation pattern is the best choice for the TT&C antenna on Orion.

b. Launch Shroud Compatibility

Of the design criteria discussed earlier in this Chapter, physical compatibility of the antenna with the launch shroud is of particular importance to the Orion. Although the Orion is being designed for launch from both the Space Shuttle and expendable launch vehicles, the restricted size of the Shuttle GAS canister places the most severe restraints on antenna design. The canister proposed for the Orion is shown in Figure 3.2. One can see that no room is available for externally mounted antennas during transport in the Shuttle. Thus, antennas on Orion will need to be one of two general types: 1) a conformal circular array around the body of the satellite, or 2) an antenna capable of being deployed on a boom from either the top or bottom of the satellite immediately after launch.

c. Solar and Environmental Effects

As mentioned, solar wind transparency is an important factor in space-based antenna design. This factor becomes particularly critical when dealing with spin-stabilized platforms such as Orion due to the transverse force which the

solar wind exerts against the satellite. Such forces may cause instability of the platform itself. Thus, solar wind prohibits antennas with large solid reflectors from being

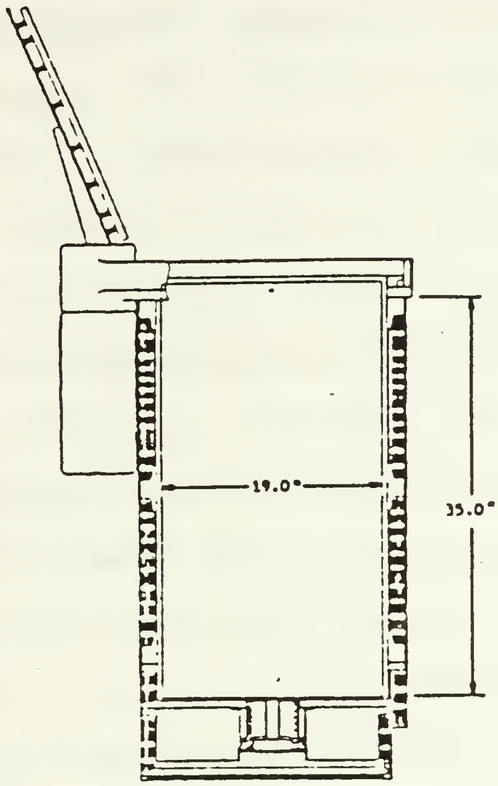

Figure 3.2 GAS Canister [Ref. 7: p. 5]

employed on Orion. Other environmental factors deal primarily with the lightweight materials used in fabrication of space-based antennas. To accommodate the environment present is space, materials need to have a low thermal expansion coefficient. Kevlar and graphite are commonly used substances having the desired thermal properties. [Ref. 8: p. 214]

B. COMMERCIALLY AVAILABLE ANTENNAS

Initial designs for the Orion mini-satellite, in keeping with the stated low cost, have stressed the use of commercially available components as much as possible. A significant portion of the research for this thesis therefore consisted of investigating commercially available TT&C antennas for their potential use on Orion. The criteria utilized for the investigation included constraints imposed by the overall design for the Orion and its ground interface, as outlined in Chapter II, and the space specific antenna design considerations as they apply to Orion, described in Sections A.1 and A.2 of this Chapter. In addition, a deliberate effort was made to keep the TT&C antenna system relatively simple as an aid in lowering the overall complexity and final production cost for the satellite.

As discussed previously, TT&C antennas for Orion must be either boom mounted on the top or bottom of the satellite, or conformally wrapped around the cylindrical body of the spacecraft. This requirement in itself drastically limits the range of TT&C antennas to be examined. The number of candidate antennas was further reduced by the combination of requirements for omni-directional pattern coverage, compatability with a spin-stabilized orbit, and circular polarization. (It should be noted that linear polarization may be used if one wishes to accept the resulting 3 dB loss.)

S-band antennas meeting these requirements incude conformal arrays of either slots or microstrip elements, and deployable antennas such as half-wave dipoles or conical log-spirals.

Of these antennas, the conformally wrapped slot array is easily the least desirable choice for Orion. Not only is a circular slot antenna overly complex, requiring an extensive network of feedlines, it also is not available off-the-shelf in a format compatible with Orion's 19 inch diameter. This results in prohibitive engineering and development costs. Although microstrip arrays are similar to slot arrays in that no commercial antenna compatible with Orion is directly available off-the-shelf, microstrip arrays exhibit two features which make them a more attractive candidate. These features are: 1) relatively simple design, which is easily configurable to a mini-satellite, and 2) ease of fabrication, both of which lead to development costs several orders of magnitude lower than those for conformal slot arrays.

When considering deployable antennas for Orion, the conical log-spiral has several advantages over half-wave dipoles. These include circular vice vertical polarization, wide bandwidth, and commercial availability of space qualified antennas mountable on Orion. The remainder of this chapter will address conformal microstrip arrays and conical log-spiral antennas in more detail as to theory, design, and utilization as a TT&C antenna on the Orion mini-satellite.

C. CONFORMAL MICROSTRIP ARRAYS

1. Theory

Microstrip antennas, at the forefront of microwave technology today, are essentially nothing more than single side etched printed circuit board radiators. They can be easily configured into arrays by combining several basic radiating elements with their associated feed networks on the same microwave printed circuit board. Conformal microstrip arrays have been used in numerous aerospace applications, and offer several advantages over conventional antennas. These include low profile, light weight, rugged construction, design flexibility, and low cost. [Ref. 9: p. 217]

The most commonly used microstrip radiating element is a rectangular patch, illustrated in Figure 3.3 below.

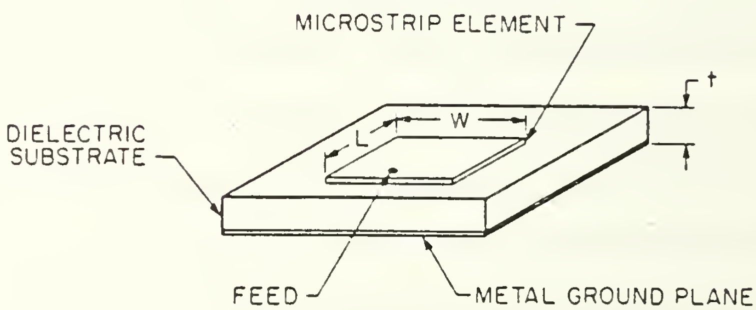

Figure 3.3 Rectangular Microstrip Element
[Ref. 10: p. 7-2]

The most critical dimension in design of a rectangular patch is the length L, which is slightly less than half a wavelength λ_d in the printed circuit substrate material.

$$L = (0.49)\,\lambda / \epsilon_r = (0.49)\lambda_d \qquad (3.1)$$

where:

λ = wavelength in free space,

λ_d = wavelength in substrate, and

ϵ_r = relative dielectric constant of substrate (specified by manufacturer).

The width w of the patch must be less than one wavelength in the dielectric substrate material. [Ref. 10: p. 7-2]

The thickness t of the board is proportional to the desired bandwidth BW of the antenna. Microstrip antennas normally have quite narrow bandwidths due to the relative thinness of commercially available microwave printed circuit boards in terms of wavelengths. This bandwidth is given by the relation:

$$BW = 128f^2t \qquad (3.2)$$

where:

BW = bandwidth in MHz (for a VSWR less than 2:1),

f = frequency in GHz, and

t = thickness in inches.

Commonly available boards come in thicknesses which are in steps of 1/64 inch (0.397mm) or 1/32 inch (0.794mm). [Ref. 10: pp. 7-7, 7-8]

The source of radiation in a microstrip patch is the electric field across the small gap between the edge of the microstep element and the ground plane directly below it. (The rear cladding of the dielectric printed circuit board serves as the ground plane.) Each slot radiates an omni-directional pattern into the half space above the ground plane. Figure 3.5 shows a side view of the microstrip radiation mechanism, while Figure 3.5 (a) and (b) display the associated normalized element radiation patterns in terms of relative dielectric constants. [Ref. 10: p. 7-5]

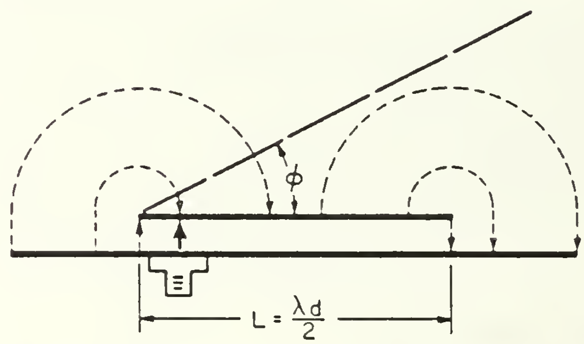

Figure 3.4 Side View of Microstrip Radiation
[Ref. 10: p. 7-6]

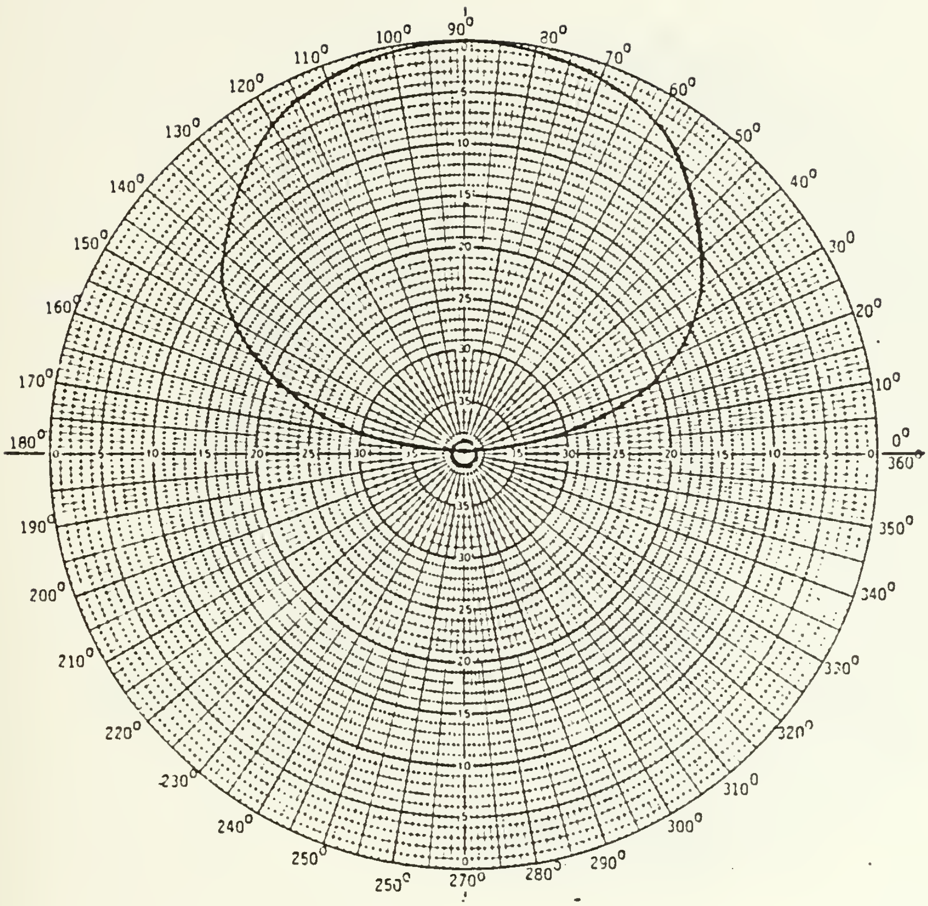

Figure 3.5 (a) E-Plane Pattern (ϵ_r=1.0)
[Ref. 10: p. 7-8]

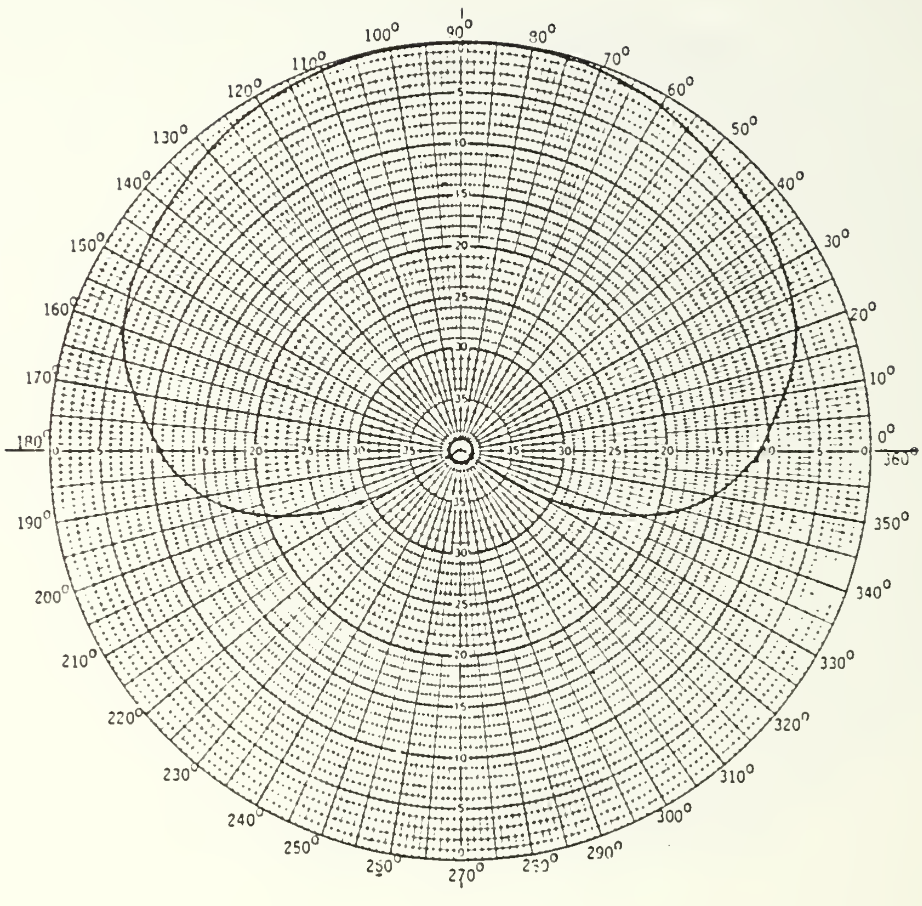

Figure 3.5 (b) E-Plane Pattern (ϵ_r =2.45) [Ref. 10: p. 7-9]

Circular polarization, the preferred mode of polarization for satellite to ground communication links, can be easily generated in microstrip radiating elements. One commonly employed method involves the use of a square patch, which is adjusted slightly off resonance through the use of a trim tab, as depicted in Figure 3.6. When the element is driven at a frequency between the resonant frequencies of the two orthogonal modes, the fields developed will be 90 degrees out of phase, and a circularly polarized signal will result. [Ref. 9: p. 218]

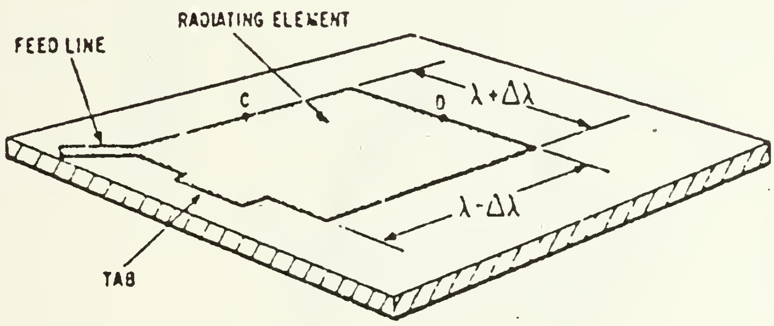

Figure 3.6 Circularly Polarized Element
[Ref. 9: p. 221]

2. Array Design For Orion

Microstrip arrays, integrating several microstrip radiating elements with a microstrip feed network on a single etched circuit board, have been proven fully capable of producing omni-directional pattern coverage from space. The omni-directional array is normally wrapped around the diameter of the missile or satellite, resulting in a a null in the radiation pattern along the spin axis [Ref. 10: p. 7-21]. Pattern coverage for cylindrical spin-stabilized satellites such as Orion is depicted in Figure 3.7. Antenna performance is unaffected by mounting on the satellite, due to the fact that the back of the printed circuit board acts as the ground plane [Ref. 10: p. 7-19].

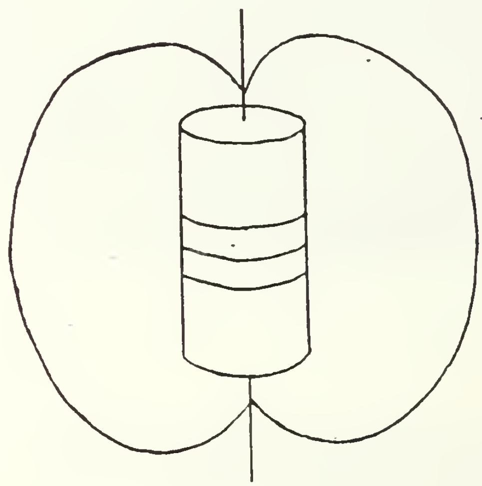

Figure 3.7 Orion Pattern Coverage

The limiting factor for omni-directional pattern coverage is the diameter of the cylinder. Figure 3.8 shows theoretical radiation pattern coverage for circular S-band microstrip arrays in terms of diameter. As can be readily seen, approximately 99.99 percent of the pattern coverage will be at a level of -8 dBi or higher for a 19 inch diameter. For Orion this would translate in practical terms to a gain of -2 to -3 dBi through most of the radiation pattern, with -8 dBi on the spin axis.

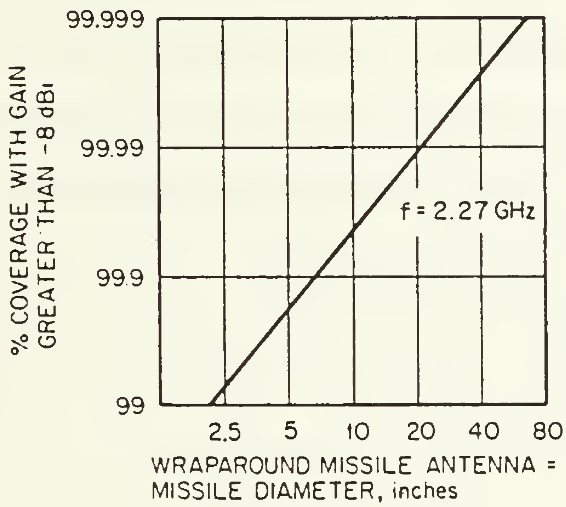

Figure 3.8 Coverage Versus Diameter [Ref. 10: p. 7-23]

For a circularly polarized microstrip array, ripple variation in the roll plane (the plane passing through the array perpendicular to the spin axis) is a function of center-to-center element spacing. In order to obtain a uniform radiation pattern in the roll plane, separation between elements should not exceed 0.7λ as shown in Figure 3.9. It should also be noted that element spacings less than 0.35λ are also undesirable, as they create unacceptable levels of mutual coupling. [Ref. 10: p. 7-21] A suitably designed array for Orion (with a circumference of 19 inches) would contain 16 elements, resulting in a spacing of 3.73 inches (94.76 mm) between elements. This equates to 0.69λ for a nominal SGLS downlink frequency of 2.2 GHz and 0.57λ for an uplink frequency of 1.8 GHz, with both values resulting in roll plane ripple of less than 2 dB.

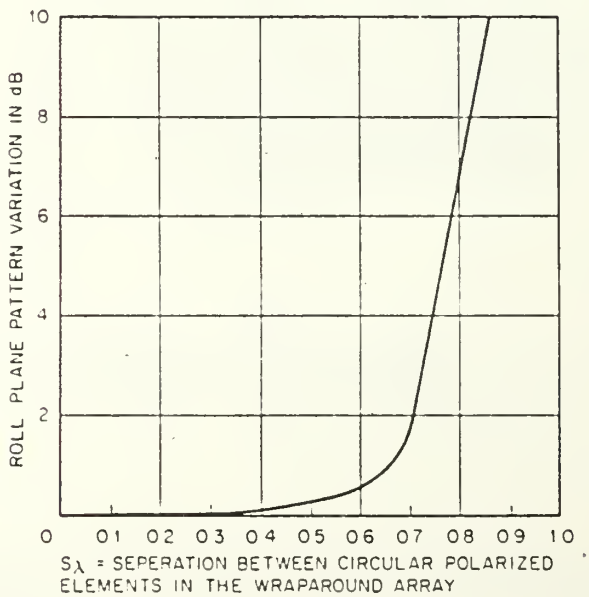

Figure 3.9 Roll Plane Variation
[Ref. 10: p. 7-23]

As has already been stated, microstrip antennas are restricted by their bandwidths. Using Equation 3.2, it can be shown that an antenna etched on a commonly available printed circuit board, 1/32 inch thick, and operated at a SGLS frequency of 2.0 GHz, would have a bandwidth of only 16 MHz. Since standard SGLS uplink and downlink frequencies are approximately 20 percent (400 MHz) apart, separate transmit and receive arrays would be required for Orion.

3. Use on Orion

Conformal microstrip arrays deserve serious consideration for selection as the TT&C antenna on the Orion mini-satellite. They offer the prime advantage of complete omni-directional pattern coverage in the roll plane, enabling the satellite to maintain communication with the ground from a broad range of orbits and trajectories. Having already flown on a number of satellites, launch vehicles, and missiles, microstrip arrays also exhibit design flexibility, low cost, and high reliability due to the fact that the entire array is etched on one continuous copper board. An added advantage is that the U.S. Navy has obtained rights to produce microstrip antennas from the U.S. Patent holder, Ball Aerospace Corporation. It would be possible to design and etch a suitable array at the Naval Postgraduate School, although qualification testing would have to be done elsewhere.

One important antenna system design factor for Orion has yet to be discussed in relation to conformal microstrip arrays. Mini-satellites have limited surface area available for antenna mounting. This design consideration stems from the power generation problem mentioned in Chapter II. Commonly available microwave printed circuit boards are 3 1/2 inches wide. Since only one array can be etched on each board, two separate boards will need to be used, requiring approximately 418 square inches, or 20 percent of Orion's total cylindrical surface area. From conversations with the NPS Orion Staff Engineer, it would be impossible to sacrifice this amount of surface area and still be able to convert a sufficient amount of solar radiation to power the satellite. It thus appears that solar power requirements preclude the use of a conformal microstrip array as the TT&C antenna on the Orion mini-satellite at this time.

D. CONICAL LOG-SPIRAL ANTENNAS

1. Theory

a. Geometry

The ground based receivers and antennas which will interface with Orion require circularly polarized signals. The conical log-spiral is a frequency independent antenna capable of providing broadband omni-directional circularly polarized radiation from space-based platforms.

Frequency independent antennas, in general, are designed by successive applications of an arbitrary scaling factor on the radiating structure. If the resulting structure is identical to the original in terms of its shape and dimensions in wavelengths, then the impedance and radiation properties of the antenna will be independent of frequency. [Ref. 10: p. 14-2].

For log-spiral antennas the arbitrary scaling factor τ is derived from a rotation of the basic structure about an axis through the origin such that the relation

$$\tau = e^{2b} \qquad (3.3)$$

is satisfied. (Here b is the expansion coefficient which will be defined later.) The log spiral is in actuality a special case of a log-periodic antenna with a period of $\log(\tau)$. When a planar log-spiral antenna is orthogonally projected onto the surface of a cone, a conical log-spiral antenna results. This projection is depicted in Figures 3.11 (a) and (b), while the geometry for a conical log spiral is shown in Figure 3.12.

The spiral arms on the antennas are drawn on a cone of revolution about the vertical axis such that a constant pitch angle α on each is maintained with the radius vector. The pitch angle is defined as the angle between the radius vector and tangent to the log-spiral arm at the point

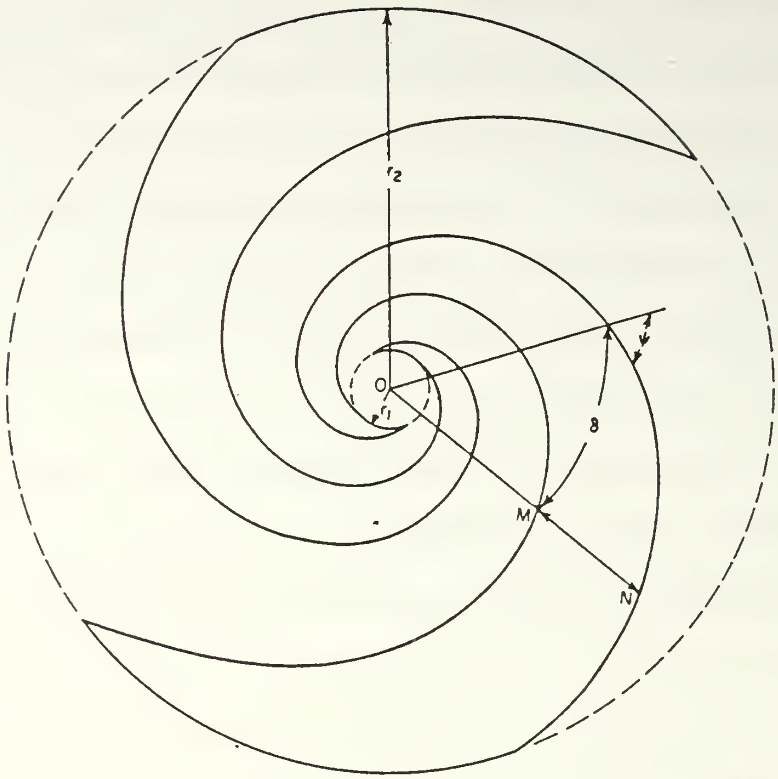

Figure 3.11 (a) Log-Spiral
[Ref. 10: p. 14.8]

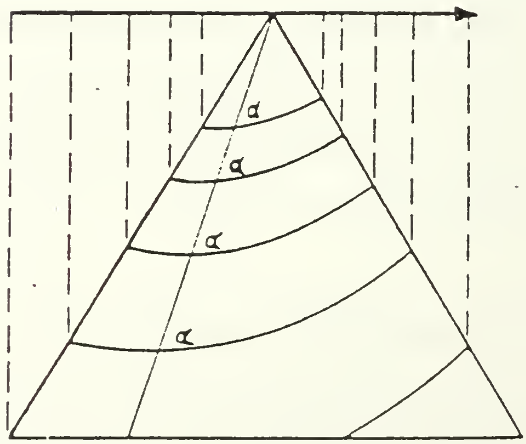

Figure 3.11 (b) Projection Onto Cone
[Ref. 11: p. 339]

of intersection. The cone angle θ and the pitch angle α are related to the expansion coefficient b by the following relation: [Ref. 10: p. 14-7]

$$\tan(\alpha) = \sin(\theta)/b \tag{3.4}$$

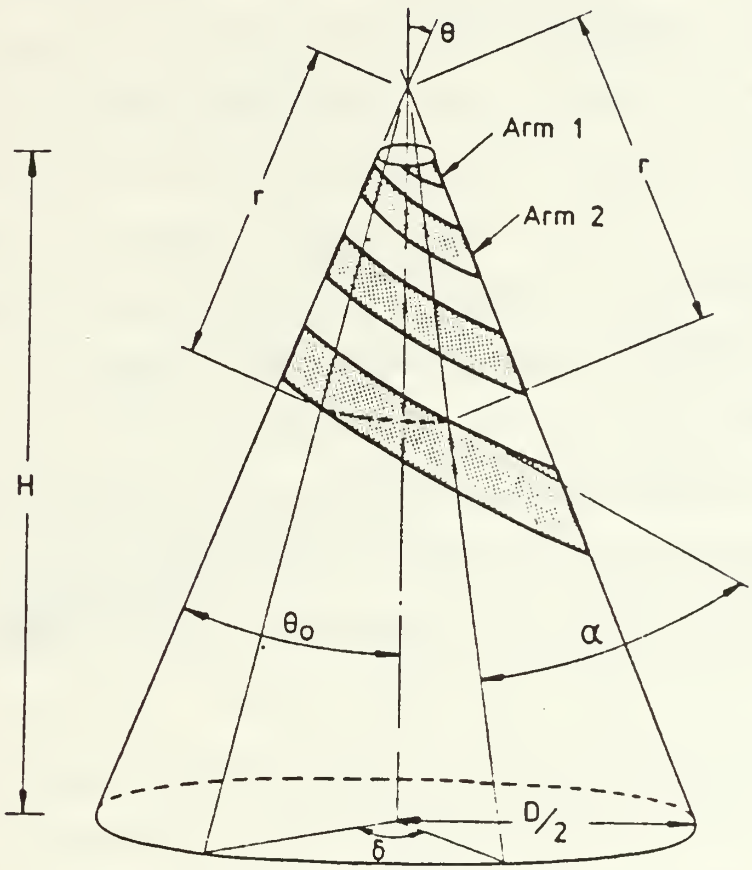

Figure 3.12 Conical Log-Spiral Geometry [Ref. 12: p. 301]

In a balanced two arm conical log-spiral antenna as pictured, the second arm is a rotation of the first arm through 180 degrees. Other critical parameters describing a conical log-spiral include the height H, base diameter D, apex diameter d, and the angular arm width δ. [Ref. 11: p. 335]

b. Radiation

Studies by Dyson have identified an active region, or effective radiating aperture, on the conical log-spiral antenna. The size and location of this active region can be determined in terms of the antenna parameters already discussed. Dyson determined that near fields which are more than 15 dB below the maximum near field amplitude in the direction of the base and 3 dB below in the direction of the apex contributed little to the overall pattern. (The radii at these points are termed a_{15}^{+} and a_{3}^{-} respectively.) The area between these points is the active region. [Ref. 13: p. 491]

In a balanced two-arm conical log-spiral antenna, out-of-phase traveling-wave currents are excited at the apex. These currents then travel in a non-radiating or transmission-line mode until they reach the active region. In the transmission-line mode there is little radiation due to the fact that the currents in the arms are out-of-phase. In the active region, on the other hand, currents are nearly in-phase, and strong coupling into space occurs. Attenuation is on the order of 7 to 10 dB per wavelength along the arms. [Ref. 10: p. 14-12]

Boundaries of the active region on a conical log-spiral antenna are depicted in Figure 3.13 as a function of included cone angle and pitch angle. By normalizing the vertical axis to the shortest wavelength of operation and the

horizontal axis to the longest wavelength, the required radii for the apex and base of the cone can be calculated.

[Ref. 13: p. 491]

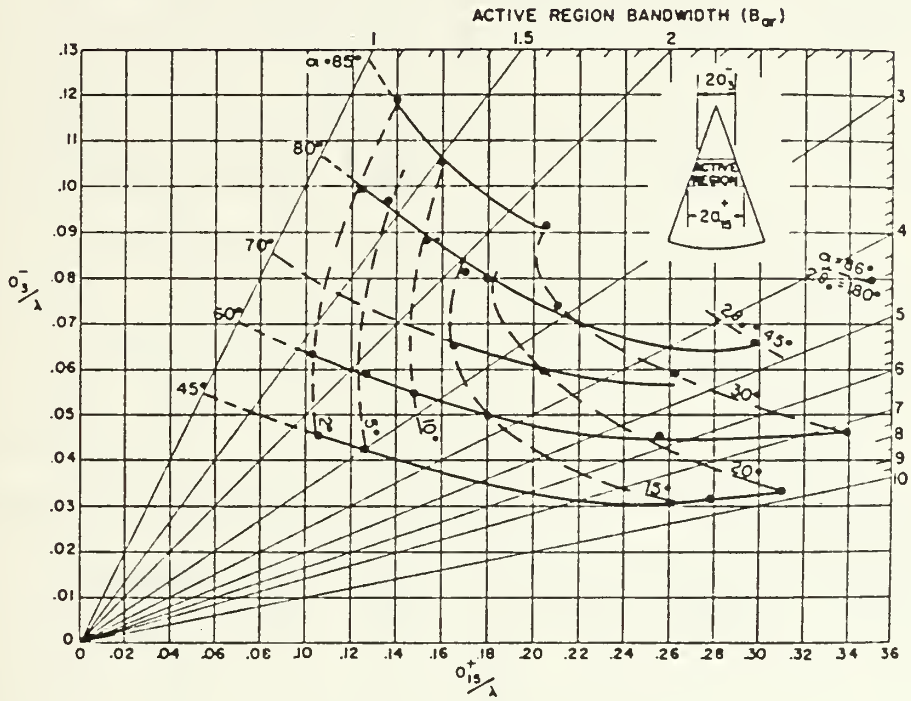

Figure 3.13 Boundaries of Active Region
[Ref. 13: p. 492]

Typical radiation patterns for conical log-spirals as a function of cone angle and pitch (or spiral angle shown in Figure 3.14. Note that relatively narrow beams are formed by small cone angles with tightly wound spirals (large α). This directivity is indicative of all turns of the arms in the active region being phased for backfire radiation.

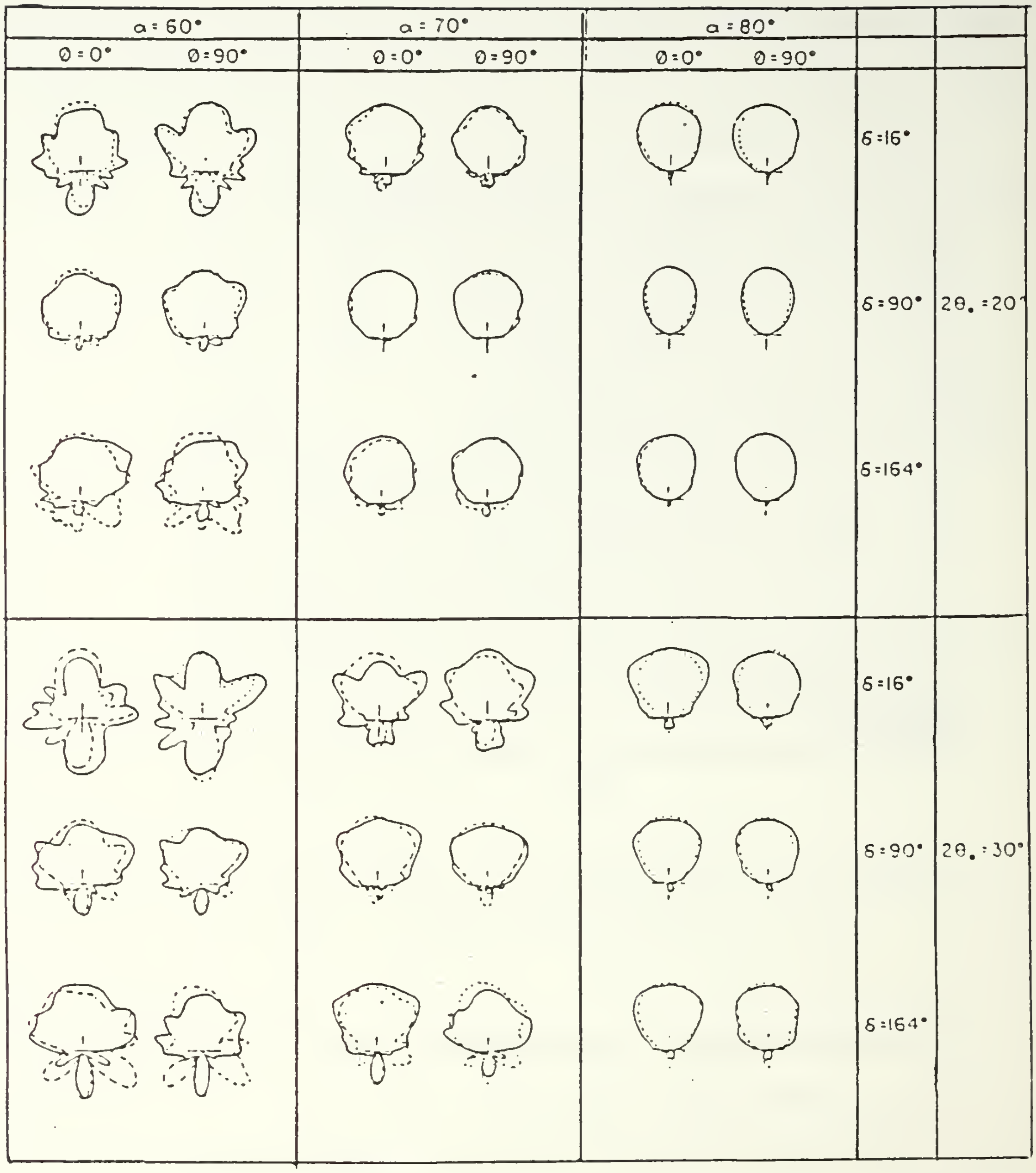

Figure 3.14 Typical Radiation Patterns
[Ref. 13: p. 497]

Broader radiation patterns are achieved by enlarging the included cone angle and reducing the rate of spiral, creating a multiple beam effect. [Ref. 13: p. 492]

2. Design For Orion

Unlike the microstrip array, where no off-the-shelf antenna meeting the design requirements for Orion existed, several conical log-spiral TT&C antennas compatible with Orion are commercially available. Of these, an S-band model offered by Rockwell International Corporation appears particularly attractive for use on the Orion mini-satellite. The Rockwell conical log-spiral TT&C antenna is fully space qualified, as it is currently in use on the DoD GPS satellite. In addition, GPS utilizes the same Motorola SGLS transponder being considered for inclusion in the Orion TT&C subsystem. Thus, adoption of the Rockwell conical log-spiral for Orion would eliminate much of the design, testing, and system integration normally required, resulting in a substantial monetary savings.

According to the manufacturer's specifications, the antenna is 6.30 inches high, has a base diameter of 4.04 inches, and weighs less than 0.63 pounds. [Ref. 14: p. 46] These dimensions are shown as a drawing in Figure 3.15. The conical log-spiral is constructed from composite laminated fiberglass, with the copper spiral arms imbedded in the fiberglass. Values for the cone angle θ, pitch angle α, and

angular arm width δ were measured on a sample antenna, and are approximately 15 degrees, 65 degrees, and 90 degrees respectively. These numbers correspond favorably to the nominal design parameters for broad beam radiation displayed previously in Figure 3.14.

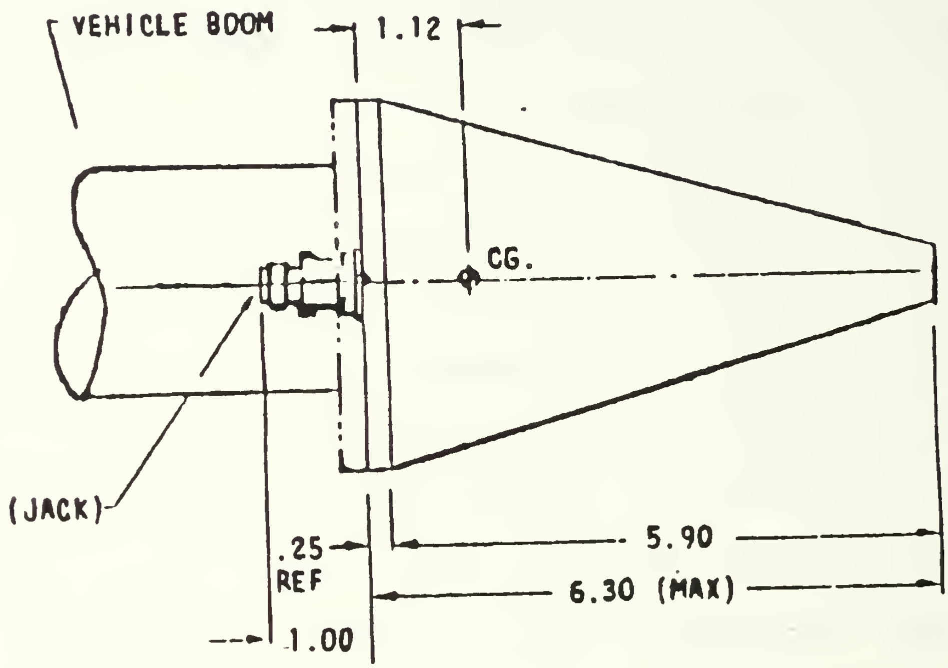

Figure 3.15 Antenna Dimensions
[Ref. 14: p. 31]

The conical log-spiral is an extremely broad band antenna. As such, only one antenna will be required for both uplink and downlink frequencies; however, this will necessitate use of a diplexer between the transmitter and receiver. Use of the diplexer, as well as isolation requirements, will be investigated in the next chapter.

The actual means of mounting the conical log-spiral TT&C antenna on Orion has yet to be determined. As mentioned, this mounting only becomes critical when designing the Orion for launch from a GAS canister. The antenna will need to be stowed beneath the top of the cylinder, in the payload module area, while inside the canister. The conical log-spiral will then be deployed on a boom after ejection from the canister. Key questions still needing to be answered at this time include: length of boom, method of boom deployment, and availability of space within the payload module for antenna stowage. A depiction of the Orion with a deployed log conical-spiral is shown below in Figure 3.16.

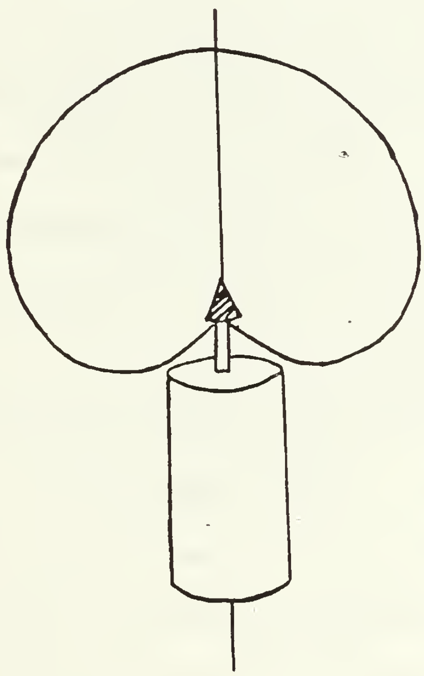

Figure 3.16 Conical Log-Spiral on Orion

IV. ANALYSIS OF CONICAL LOG-SPIRAL TT&C ANTENNA

A. PERFORMANCE CRITERIA

1. Space Qualification Testing

The Rockwell conical log-spiral TT&C antenna undergoes a strenuous set of acceptance tests before it is certified as qualifed for space. These tests include a random vibration test, which determines the capability of the antenna to function during launch, a thermal vacuum test, where each antenna is screened for ability to withstand extremes of hot and cold in space, and full measurement of antenna radiation patterns. In addition, the electrical performance, or voltage-standing-wave-ratio (VSWR), of the antenna is measured throughout the uplink and downlink SGLS frequency bands before, during, and after each test. Minimum performance standard for the VSWR throughout the testing is less than or equal to 1.5:1. [Ref. 14: pp. 8-21]

2. Pattern Coverage

The radiation pattern for the Rockwell conical log-spiral TT&C antenna is essentially omni-directional, as indicated by the manufacturer's specifications which call for a measured half-power beamwidth greater than 90 degrees. Maximum gain for both uplink and downlink frequencies must be greater than +4.0 dBi, which is significantly higher than

the theoretical value of -2.0 dBi for the conformal microstrip array. Figure 4.1 displays an example of a measured radiation pattern for a Rockwell conical log-spiral at a typical SGLS frequency of 2227.5 MHz.

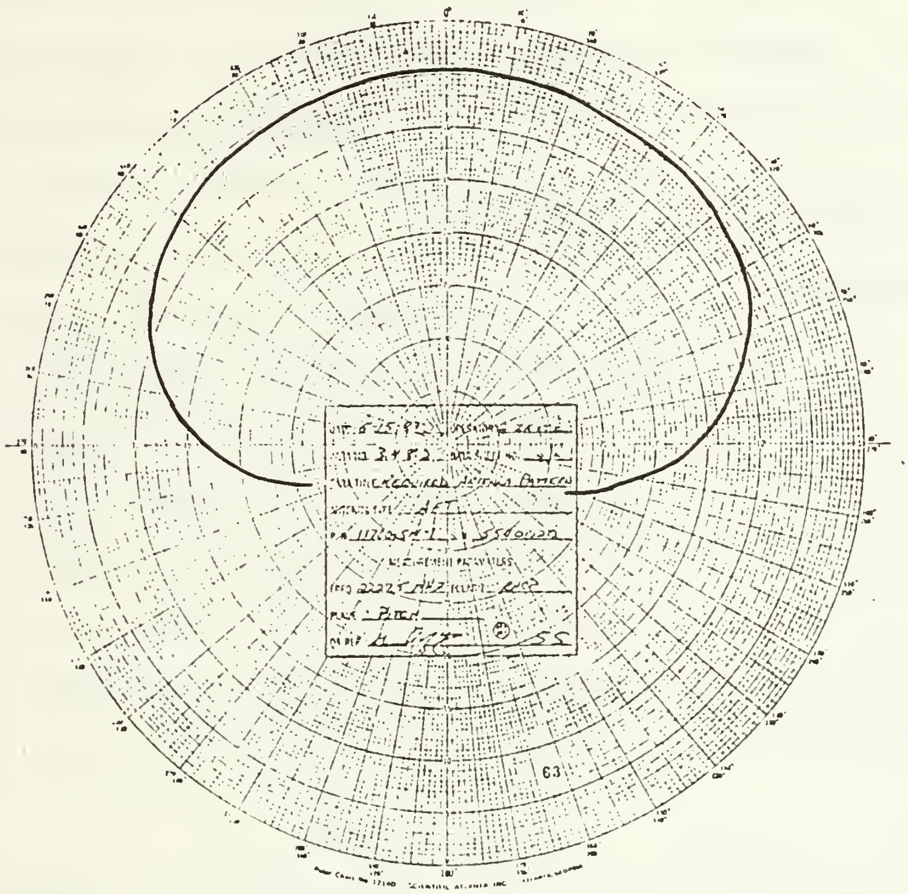

Figure 4.1 Measured Radiation Pattern
[Ref. 15: p. 63]

The gain on this polar plot has been normalized such that the 10 dB line equates to 0 dBi, or isotropic radiation. Thus, the observed gain for the tested conical log-spiral is approximately +5.4 dBi on the spin axis (θ = 0 degrees) and -6.0 dBi where the pattern intersects the roll plane (θ = 90 or 270 degrees). The beamwidth of this antenna pattern is 120 degrees, 30 degrees greater than the manufacturer's specified value [Ref. 14: pp. 63-64]. Omni-directional radiation patterns such as the one depicted appear compatible with the requirements for the Orion mini-satellite.

B. SPACE-GROUND LINK CALCULATIONS

1. General

In order to insure that the conical log-spiral antenna will function adequately on Orion and interface successfully with AFSCN ground stations, and with SGLS, it is necessary to investigate the satellite-ground station power margins for both uplink and downlink. There are a large number of factors which contribute to calculation of these margins, the most significant of which are listed below. [Ref. 5: p. 5.1-1]

1. Satellite transmitter power, line loss, and antenna gain (effective radiated power - ERP).
2. Space loss, atmospheric attenuation, and polarization loss.
3. Ground transmitter power and antenna gain (ERP).
4. Modulation Index.

5. Receiver sensitivity.

6. Required signal to noise ratio (SNR).

2. Ground Station To Satellite Uplink

The first step in calculation of the uplink SGLS service power margins is to compute the total power available at the input to the satellite receiver. This is determined by consideration of ground station effective radiated power (ERP), losses through space and the atmosphere, and the satellite antenna gain (items 1 through 3 in paragraph 1 above).

Next, the available power for the carrier and for the range and command tones SGLS services must be determined. SGLS service power levels are a function of the modulation index (item 4), which for uplink is controlled by push button at the AFSCN ground station [Ref. 5: p. 5.1-3]. Indices available are 0.125 and 0.30 radians for range and 0.30 and 1.00 radians for command service. The selection of these modulation indices provide different distributions of carrier and sideband power within the baseband signal, resulting in modulation losses which can readily be calculated. The available SGLS service power is then computed by subtracting the modulation losses from the total available power. The actual modulation loss computations used for link calculations in this chapter are enclosed in the Appendix. [Ref. 5: p. 5.1-3]

Third, the minimum signal strength required at the satellite receiver must be determined (item 5 above). For the Motorola receiver, required signal strength was given in the manufacturer's specifications based on a minimum allowable bit error rate (BER).

Finally, the last step in computation of the service power margins is to subtract the required signal strength at the receiver from the available power of the various SGLS services. [Ref. 5: p. 5.1-3].

<u>Ground Station Signal Characteristics/Assumptions</u>:

Frequency (SGLS Ch. 10)...............1799.756 MHz

Command bit rate......................1 kbps

Command modulation index(note 1)......0.30 radians

Ranging modulation index(note 1)......0.30 radians

Transmitter power(note 2).............1.0 kW/+60.0 dBm

Antenna gain(note 3)..................+31.4 dB

note 1: 0.30 radians is the most common uplink modulation index.

note 2: 1 kW is standard link analysis value; however AFSCN transmitters are capable of radiating up to 10 kW.

note 3: Antenna gain is for 14 ft dish (worst case for AFSCN TT&C antennas).

<u>Orion Characteristics/Assumptions</u>:

Orbit (circular)......................400 nmi

Antenna gain(note 1)..................-6.0 dBi

Antenna polarization..................RHCP

Line losses (nominal).................-3.0 dB

note 1: Antenna gain based on worst case measured coverage on roll plane.

Required power at receiver: (note 1)

Carrier..............................-113 dBm

Command..............................-103 dBm

Range................................-105 dBm

note 1: Required signal power from Ref. 15, pp. 7-8. (assumes a BER of 10^{-5} for threshold SNR)

Uplink Calculation: [Ref. 5: p. 5.1-6]

Total Available Power:	Loss	Gain
Transmitter power		+60.0 dBm
Ground antenna gain		+31.4 dB
Space loss (note 1)	-166.3 dB	
Polarization loss	0.0	
Atmospheric attenuation	-1.0 dB	
Sat. antenna gain	-3.0 dB	
Sat. line loss	3.0 dB	
	-173.3 dB	+91.4 dB

Total received power = -81.9 dBm

note 1: Space loss based on worst case maximum slant range value (400 nmi orbit with 5 degrees ground antenna elevation).

SGLS Service Power:	Carrier	Command	Range
Modulation loss(note1)	-0.6 dB	-14.0 dB	-10.7 dB
Net service power	-82.5 dBm	-95.9 dBm	-92.6 dBm

note 1: see Appendix.

Required receiver power:	-107 dBm	-105 dBm	-105 dBm
Power margins:	+24.5 dBm	+9.1 dBm	+12.4 dBm

3. Satellite to Ground Station Downlink

Computation of the downlink SGLS service power margins is quite similar to the uplink calculations just completed. First, the total power available at the input to the ground receiver must be determined by consideration of satellite effective radiated power (ERP), space and atmospheric losses, and the ground antenna gain (items 1 through 3 in Section 1). [Ref. 5: p. 5.1-2]

Then, as before, the available power for the carrier and for the SGLS downlink services of range and telemetry must be determined by calculating power losses due to modulation. Modulation indices for downlink, used to calculate these losses, must be preset on the Motorola transponder prior to launch. Any value from 0.10 to 0.50 radians for range and 0.80 to 1.80 radians for telemetry data may be selected [Ref. 16: pp. 4-5].

The ground receiver noise power, or KTB noise floor of the receiver, is computed by adding Boltzman's constant, the antenna noise factor, and the noise bandwidth. The available SNR can then be calculated by subtracting the total available service power from the receiver noise power. Finally, the last step in computation of the service power margins is to subtract the required SNR, given in the ground station specifications, from the calculated SNR.

Orion Signal Characteristics/Assumptions:

Frequency (SGLS Ch 10, Carrier 1)......2247.5 MHz

Ranging modulation index (note 1)......0.30 radians

Subcarrier (note 2)....................1.024 MHz

Telemetry modulation index...........1.40 radians

Telemetry data signal................32 kbps, NRZ-L

Transmitter power......................3 W/34.8 dBm

(All other satellite characteristics same as uplink)

note 1: modulation indices chosen in order minimize losses (Appendix A).

note 2: calculations based on assumption of low data rate telemetry signal from Orion

Ground Station Characteristics/Assumptions:

Receiver noise power (by SGLS service):

	Telem.	Carrier	Range
Boltzmans const.(dBm/Hz)	-198.6	-198.6	-198.6
Antenna noise factor(note 1)	+25.8 dB	+25.8 dB	+25.8 dB
Noise bandwidth (note 2)			
Telemetry - 32 kHz	+45.1 dB		
Carrier - 5 kHz		+37.0 dB	
Ranging - 12 Hz			+10.8 dB
Total noise power	-127.7dBm	-135.8dBm	-162.0dBm
Required SNR:	+14.0dB	+6.0dB	+26.6dB
(notes 2 and 3)			
Required receiver power:	-113.7dBm	-129.8dBm	-135.4dBm

(All other ground station parameters same as uplink)

note 1: Antenna noise factor based on 376 degrees K for 14 ft TT&C antenna

note 2: Discussion of noise BW and SNR for AFSCN receivers found in Chapter 2 and 3 of Ref. 5.

note 3: Threshold telemetry SNR assumes bit error rate (BER) of 10^{-5}. [Ref. 5: p. 2.3-20]

Downlink Calculations: [Ref. 5: pp. 5.1-11, 5.1-12]

Total Available Power:	Loss	Gain
Sat. transmitter power		+34.8 dBm
Sat. line loss (nominal)	-3.0 dB	
Sat. antenna gain	-6.0 dB	
Space loss	-168.5 dB	
Polarization loss	0.0	
Atmospheric loss	-1.0 dB	
Ground antenna gain		33.5 dB
	-178.5 dB	+68.3 dBm

Total received power = -110.2 dBm

SGLS Service Power:	Telem.	Carrier	Range
Modulation loss (note 1)	- 2.5dB	- 5.1dB	- 18.5dB
Net service power	-112.7dBm	-115.3dBm	-128.7dBm

note 1: See Appendix.

Power margins:			
Receiver noise power	-127.7dBm	-135.8dBm	-162.0dBm
Service power	-112.7dBm	-115.3dBm	-128.7dBm
SNR (calculated)	+15.0dB	+20.5dB	+33.3dB
SNR (required)	+14.0dB	+ 6.0dB	+26.6dB
Margins	+ 1.0dB	+14.5dB	+ 6.7dB

Positive SGLS service power margins were obtained for both uplink and downlink using the conical log-spiral TT&C antenna on Orion. The above link calculation analysis was conducted from a worst case scenario to the maximum extent possible. Thus it is highly likely that larger power margins may exist in some cases.

C. RECEIVER-TRANSMITTER ISOLATION

1. Requirements

One facet of the conical log-spiral antenna and its potential use as part of the Orion TT&C subsystem has yet to be investigated, namely receiver-transmitter isolation. Isolation is particularly critical when considering the conical log-spiral, due to the antenna's extremely broad bandwidth. In addition, the possibility of leakage of the transmitted signal into the receiving path is increased when only one antenna is used for both reception and transmission, as is the case on Orion.

The primary method of blocking leakage is through the use of an input filter on the front end of the receiver. The Motorola SGLS receiver has a four pole preselector filter with the following rejection characteristics: [Ref. 16: pp. 7-8]

Bandwidth	Rejection
24 MHz	3 dB
40 MHz	20 dB
120 MHz	60 dB

On initial inspection, this is a sufficient amount of rejection, taking into account the substantial frequency difference between SGLS uplink and downlink bands (greater 400 MHz).

Potential isolation problems arise when the possibility of spurious or out-of-band transmisions is considered. The Motorola SGLS transmitter complies with Military Standard 461. As such, spurious transmissions are -45 dBc (dB relative to carrier) within ± 2 1/2 MHz of the carrier and -60 dBc outside this interval. [Ref. 16: p. 6]

2. Use of Diplexer

When a single antenna system is employed, it is necessary to physically separate the reception and transmission paths through the use of a diplexer [Ref. 2: p. 283]. Diplexers function in two ways: 1) they allow transmitted signals to be radiated into space through the antenna, while isolating the receiver from the transmitted power, and 2) they allow incoming signals from the antenna to be sent to the receiver, while again isolating the receiver from the transmitter [Ref. 18: pp. 236-238]. Characteristics for the diplexer employed by Motorola in single antenna systems are given in Table 4-1.

TABLE 4-1

DIPLEXER INSERTION LOSS AND ISOLATION
[Ref. 17: p. 10]

Frequency (MHz)	Antenna to Receiver	Xmtr to Antenna	Xmtr to Receiver
1750	----	$\geq$ 70 dB	$\geq$ 70 dB
f_r-70	$\geq$ 35 dB	$\geq$ 70 dB	----
f_r-5	$\leq$0.8 dB	$\geq$ 70 dB	$\geq$ 70 dB
f_r	$\leq$0.8 dB	$\geq$ 70 dB	$\geq$ 70 dB
f_r+5	$\leq$0.8 dB	$\geq$ 70 dB	----
f_r+70	$\geq$ 35 dB	$\geq$ 70 dB	$\geq$ 70 dB
1850	----	$\geq$ 70 dB	$\geq$ 70 dB
2200	$\geq$ 90 dB	----	$\geq$ 90 dB
f_t-5	$\geq$ 90 dB	$\leq$0.4 dB	$\geq$ 90 dB
f_t	$\geq$ 90 dB	$\leq$0.4 dB	$\geq$ 90 dB
f_t+5	$\geq$ 90 dB	$\leq$0.4 dB	$\geq$ 90 dB
2300	$\geq$ 90 dB	----	$\geq$ 90 dB

As a further verification that sufficient receiver-transmitter isolation can be obtained for Orion, using a conical log-spiral antenna and a Motorola SGLS transponder and diplexer, it is necessary to compute whether or not the receiver is sensitive to: 1) downlink transmissions, and 2) out-of-band transmissions.

Receiver isolation at transmit frequency:

Transmitter power (3W)	+34.8 dBm
Modulation loss (carrier)	- 5.2 dB
Diplexer isolation loss (xmtr to receiver)	-90.0 dB
Receiver rejection (out-of-band)	-60.0 dB
Total power available	-120.3 dBm
Receiver sensitivity (acquisition) [Ref. 16: pp. 7-8]	-107.0 dBm
Isolation	+13.3 dB

Transmitter isolation at receive frequency:

Transmiter power (3W)	+34.8 dBm
Modulation loss (carrier)	- 5.1 dB
Out-of-band transmissions	-60.0 dBc
Diplexer isolation (xmtr to receiver)	-70.0 dB
Total power available	-100.3 dBm
Receiver sensitivity	-107.0 dBm
Isolation	- 6.7 dBm

As can be seen, the Motorola receiver is sufficiently isolated (greater than 13 dB) from onboard transmissions at the transmit frequency. The potential exists, however, for the receiver to lock-on to spurious out-of-band transmissions. Even though the above analysis was based on a worst case approach, it is recommended that a 20 dB notched filter

be inserted into the path between the transmitter and the receiver to alleviate this possibility.

V. CONCLUSION

A. SUMMARY

This thesis has sought to undertake a preliminary investigation into the design requirements for the TT&C antenna system on the NPS Orion mini-satellite. Initially, a set of design constraints was developed through an analysis of the characteristics of the satellite itself, including launch vehicles, orbital profiles, and ground stations. Utilizing these constraints, two commercially available TT&C antennas then appeared particularly well suited to use on Orion: the conformal microstrip array and the conical log-spiral. After closer examination, the conical log-spiral was chosen as the primary candidate for the TT&C antenna on the Orion mini-satellite.

The conical log-spiral is a low cost, space-qualified off-the-shelf antenna capable of providing broadband omni-directional radiation compatible with the system requirements for Orion. The latter portion of this thesis consists of an analysis of the performance of the Orion TT&C subsystem utilizing the conical log-spiral antenna. Areas investigated were pattern coverage, space-ground link power margins, and transmitter-receiver isolation.

B. RECOMMENDATIONS

The majority of the work in this thesis consists of developing a set of design criteria for the TT&C antenna system on the Orion and in determining whether or not a commercially available antenna would meet the criteria. As such, much work needs to be completed before the satellite antenna package is fully mission capable. Primary concerns at this time for the conical log-spiral include physical mounting of the antenna on the spacecraft and means of stowage during launch.

One area yet to be investigated is that of modeling the conical log-spiral antenna on a computer. Numerical techniques for log-spiral antennas have been developed by Yeh and Mei, and are discussed in IEEE Transactions on Antennas and Propagation (see bibliography).

It also seems prudent for NPS to procure a Rockwell conical log-spiral antenna in the near future. This antenna could be purchased prior to undergoing qualification testing at a substantial savings. The author, as part of the research for this paper, has investigated use of testing facilities at the Strategic Systems and Sciences Division of the Naval Station at Seal Beach, California. It is recommended that the conical log-spiral be mounted on a mockup of the Orion and fully tested at Seal Beach, to include thermal vacuum testing, vibrational load testing, imput impedance, VSWR, and measurement of radiation patterns.

More investigation is required in the area of transmitter-receiver isolation in order to insure the need for additional attenuation. Once the decision to employ the Motorola SGLS transponder is finalized, it is recommended that face-to-face coordination be conducted with Motorola on this matter.

Finally, more design work and more research should be done concerning the second candidate TT&C antenna for the Orion, the conformal microstrip array. A more detailed design for a microstrip array needs to be made. If warranted, an array should be built and tested. In addition, the solar power/surface area problem requires further investigation. The conformal microstrip array would be a viable alternative TT&C atenna for Orion if the amount of surface area required for solar power conversion could be reduced, possibly through te use of GaAs technology.

APPENDIX

MODULATION LOSS COMPUTATIONS

1. Uplink [Ref. 5: p. 5.1-5]

The power losses due to modulation for the various uplink SGLS services can be calculated as follows:

let:

MLc	=	carrier modulation loss (dB)
MLcmd	=	command tones modulation loss (dB)
MLprn	=	range service modulation loss (dB) (prn is pseudo random noise)
J_0	=	zero order Bessel function (note 1)
J_1	=	first order Bessel function (note 1)
βcommand	=	modulation index for command tones (radians)
βprn	=	modulation index for ranging service (radians)

then:

$$\text{MLc} = 10 \log J_0^2 (\beta\text{command}) \cos^2(\beta\text{prn}) \tag{A.1}$$

$$= 10 \log J_0^2 (0.30) \cos^2(0.30)$$

$$= -0.20 - 0.40 = \underline{-0.60 \text{ dB}}$$

$$\text{MLcmd} = 10 \log 2J_1^2 (\beta\text{command}) \sin^2(\beta\text{prn}) \tag{A.2}$$

$$= 10 \log 2J_1^2 (0.30) \sin^2(0.30)$$

$$= -13.57 - 0.40 = \underline{-13.97 \text{ dB}}$$

$$\text{MLprn} = 10 \log J_0^2 (\beta\text{command}) \sin^2(\beta\text{prn}) \tag{A.3}$$

$$= 10 \log J_0^2 (0.30) \sin^2(0.30)$$

$$= -0.20 - 10.59 = \underline{-10.79 \text{ dB}}$$

2. <u>Downlink</u> [Ref. 5: p. 5.1-10]

The downlink modulation losses can be determined using similar computations:

let: MLtlm = subcarrier telemetry modulation loss (dB)

βsc = subcarrier modulation index (radians) (note 2)

Then: MLc $= 10 \log J_0^2 (\beta sc)\, J_0^2 (\beta prn)$ (A.4)

$= 10 \log J_0^2 (1.40)\, J_0^2 (0.30)$

$= -4.93 - -.20 = \underline{-5.13 \text{ dB}}$

MLtlm $= 10 \log 2J_1^2 (\beta sc)\, J_0^2 (\beta prn)$ (A.5)

$= 10 \log 2J_1^2 (1.4)\, J_0^2 (0.30)$

$= -2.31 = 0.20 = \underline{-2.51 \text{ dB}}$

MLprn $= 10 \log 2J_1^2 (\beta prn)\, J_0^2 (\beta sc)$ (A.6)

$= 10 \log 2J_1^2 (0.30)\, J_0^2 (1.40)$

$= -13.57 - 4.93 = \underline{-18.50 \text{ dB}}$

note 1: Values for Bessel functions in dB are from Table 5.1-3 in Ref. 5: p. 5.1-17.

note 2: Subcarrier = 1.024 MHz (low speed telemetry signal)

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